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COMPLEMENTARY PRODUCTS AND DEVICES

ANALYSIS OF MAXIMUM ANGLE OF MISMATCH BETWEEN HALF COUPLINGS OF A MAGNETIC CLUTCH AND HIGHLY COERSIVE PERMANENT MAGNETS

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A procedure is proposed for analysis of maximum mismatch angle between the half couplings of a magnetic clutch and highly coersive permanent magnets (formed from alloys of rare-earth elements – samarium-cobalt and neodium-iron-boron) during the start-up of an asynchronous motor is proposed for the design of hermetically sealed machines (pumps, compressors, mixers, etc.).

In hermetically sealed machines with a magnetic clutch (pumps, vacuum cleaners, compressors, mixers), the driving and driven parts are coupled elastically one with the other, and are displaced relative to one another by an angle that varies during movement (the mismatch angle of the poles of the magnetic clutch).

Prior to start-up of the driving asynchronous electric motor, the magnets of a cylindrical magnetic clutch are situated coaxially, and the half couplings opposite one another. The forces of interaction between the magnets are directed toward the center of the axis of rotation of the clutch along lines connecting the centers of the poles of the magnets. The torque of the clutch is equal to zero in this position.

During start-up, the driving half couple, which is mounted on the shaft of a driving electric motor, is turned through a certain angle, while the driven half clutch, which is mounted on the shaft of the effective member of the machine, remains in place, since the connection between the half couplings is not rigid. Moreover, the centers of the poles of the magnets are also displaced relative to one another by this same angle, and the directions of the interaction forces of the magnets are changed – tangential components of the interaction forces are manifested. A torque develops in the clutch under the action of all tangential magnetic forces. When the torque of the clutch is greater than the torques created by the resistance forces (friction, load, and inertia), the driven half coupling is withdrawn beyond the driving half coupling, and an additional load develops on the driving electric motor, which lowers its dynamic torque. The acceleration of the driving half coupling is reduced, and the driven half coupling approaches the driving half coupling. As a result, the load, mismatch angle, and torque of the clutch (acting on the driving half clutch) are reduced, and the driving motor is again accelerated, leading to an oscillatory process.

The maximum torque transferred by the clutch should exceed the in-service torsional moments due to the resistance forces in order to avoid breaking of the magnetic bond between the half couplings (rotations of the half couplings with different frequencies, resulting in a marked reduction in the torque being transferred). It should be pointed out that after the pause associated with restoration of the broken magnetic bond, the torque of the clutch is fully restored – i.e., the clutch can be used as a protective link.

After acceleration from rest, the torque transferred by the clutch is reduced (consequently, the mismatch angle is also reduced) due to disappearance of acceleration of the rotating masses, and the effective operating regime of the clutch and machine is established.

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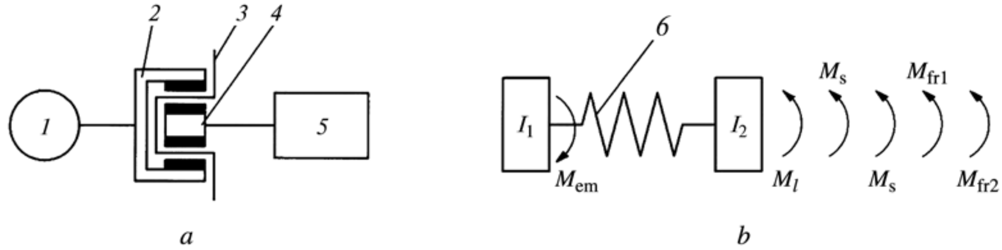

Fig. 1. Two-mass scheme with elastic member: *a*) diagram of machine with magnetic clutch; *b*) computational scheme; *1*) electric motor; *2*) driving half coupling; *3*) screen; *4*) driven half coupling; *5*) actuating mechanism; *6*) elastic member – magnetic clutch.

The elastic character of the magnetic bond between the half couplings dictates development of relative oscillations between the couplings, particularly during start-up and shutdown, as well as during conversion from one steady-state operating regime to another. Consideration of transitional processes, especially during start-up, is required when selecting the torque of the magnetic clutch for assigned parameters of the machine and the characteristic of the electric motor.

In analyzing dynamic processes in a machine with a magnetic clutch, the following basic positions are considered: the electric motor with its driving parts, and the actuating mechanism are treated as localized masses; forces and moments are applied to these localized masses; only one elastic member is contained within the machine – the clutch; and the inertial members are not deformed, i.e, are absolutely rigid.

In analyzing the dynamics of a machine with a magnetic clutch, all moments of inertia and the effective moments are usually brought forward to the driving and driven half couplings [1], since the stiffness of the coupling of the magnetic clutch is approximately two orders lower than the stiffness of the shafts. The natural vibration frequency of the other elastic members of the machine appreciably exceeds the vibration frequency of the magnetic clutch, and does not influence the parameters of its oscillatory process. In that case, it is possible to adopt a two-mass computational scheme with an elastic member characterized by the moments of interaction of the half couplings of the magnetic clutch (Fig. 1).

The system of motion equations for the machine consists of equations of the moments for each of the masses (moments of inertia):

$$\left.\begin{aligned} \frac{I_1}{p}\frac{d\omega_1}{dt} &= (M_\mathrm{em} - M_0) - M - 0.5M_\mathrm{s} - M_\mathrm{fr1}; \\ \frac{I_2}{p}\frac{d\omega_2}{dt} &= M - 0.5M_\mathrm{fr2} - M_l, \end{aligned}\right\} \tag{1}$$

where $(M_\mathrm{em} - M_0)$ is the mechanical torque of the electric motor in N·m; M_em is the electromagnetic torque of the electric motor in N·m; M_0 is the no-load torque of the electric motor in N·m; M is the torque transferred by the clutch during displacements of the half couplings in N·m; M_s is the braking torque of the screen in N·m; M_fr1 and M_fr2 are the frictional torques of the half couplings against the medium in N·m; M_l is the load-induced torque in N·m; I_1 (I_2) is the equivalent moment of inertia of the driving (driven) parts in kg·m^2; p is the number of poles of the electric motor; $d\omega_1/dt$ ($d\omega_2/dt$) is the electric acceleration of the driving (driven) half couplings in sec^{-2}; and ω_1 (ω_2) is the electrical rotational speed of the driving (driven) half coupling in rps.

The torque M transferred by the magnetic clutch depends on the angle of mismatch between the half couplings.

Magnetic clutches are usually employed for pumps, mixers, extractors, and gas blowers, where the effective domain is separated from the surrounding medium, and the driving half coupling and motor are situated in an air medium where the frictional torque M_fr1 is small and disregarded. The driven half coupling in the effective domain is located above the level of the fluid in a gaseous medium, or in an aqueous fog; the magnitude of the frictional moment of the smooth-wall cylindrical driven half coupling against the fluid, and frictional torque M_fr2 can also be disregarded.

In system of equations (1), the braking torque M_s of the screen will depend on the loss of power in the screen, which is proportional to the rotational speed of the machine. The effects of the screen on both half couplings are equal in terms of magnitude, and are created by the oscillations of the half couplings. If the screen is fabricated from a non-conducting material, no eddy currents are induced in it, and, consequently, no braking torque develops in the screen.

The torque M_{em} of the electric motor can be determined most accurately by solving a system of differential equations with consideration of the electromagnetic processes [2]; use of this method is suppressed, however, by the labor intensiveness of the analytical solution. A simplified method is therefore frequently utilized –graphical plotting of the torque of the electric motor at five points (start-up, minimal, maximal, and nominal torques, and the ideal no-load torque and the slips corresponding to them), which are cited in electric-motor catalogues. When the speed-torque characteristic of the electric motor, which is plotted from catalogue data, is used, the system of differential motion equations of the machine assumes the form:

$$\left.\begin{aligned} &\frac{I_1}{p}\frac{d\omega_1}{dt} = (M_{em} - M_0) - M_{max}\sin(\alpha_1 - \alpha_2) - 0.5M_s;\\ &\frac{I_2}{p}\frac{d\omega_2}{dt} = M_{max}\sin(\alpha_1 - \alpha_2) - 0.5M_s - M_l;\\ &M_{em} = f(\omega_1), \end{aligned}\right\} \tag{2}$$

where α_1 and α_2 are the electrical turn angles of the driving and driven half couplings in rad; $(\alpha_1 - \alpha_2)$ is the electrical mismatch angle of the poles of the half couplings in rad; and M_{max} is the maximum static torque of the magnetic clutch in N·m.

Similitude theory and writing of the equations in relative units can be employed for convenience of analysis of system of Eqs. (2), for which the following base values can be introduced [3]: the torque is assumed equal to the nominal torque of the electric motor $M_{b1} = M_{non}$; the moment of inertia $I_{b1} = I_1/p$; the electrical rotational speed $\omega_1 = (M_{b1}/I_{b1})^{1/2} = (M_{nom}p/I_1)^{1/2}$; the time $t_{b1} = 1/\omega_{b1}$; and the electrical turn angle $\alpha_{b1} = \omega_{b1}t_{b1} = 1$.

After introduction of the base values and simple mathematical transformations of system of equations (2), we obtain a new system of differential equations in relative units, which describes the dynamic process of a generalized machine with a magnetic clutch in a transitional regime:

$$\left.\begin{aligned} &\frac{d\omega_1^r}{dt^r} = (M_{em}^r - M_0^r) - M_{max}^r\sin(\alpha_1^r - \alpha_2^r) - 0.5M_s^r;\\ &\frac{d\omega_2^r}{dt^r} = \frac{I_1}{I_2} - M_{max}^r\sin(\alpha_1^r - \alpha_2^r) - \frac{I_1}{2I_2}M_s^r - \frac{I_1}{2I_2}M_l^r;\\ &M_{em}^r = f(\omega_1^r). \end{aligned}\right\} \tag{3}$$

Investigation of system of equations (3) is simplified considerably, since the ratio of the moments of inertia I_1/I_2 enters into only one of the equations.

Analyzing Eqs. (3), it is possible to conclude that the transitional process of a machine with a magnetic clutch and asynchronous electric motor depends on the following dimensionless parameters: $\Pi = \omega^r - \omega_0/\omega_{b1} = 314/[(M_{nom}p)/I_1]^{1/2}$ is the relative rotational speed (here, ω_0 is the electrical synchronous rotational speed in sec^{-1}); $\Pi_I = I^r = I_1/I_2$ is the relative moment of inertia; $\Pi_c = M_{max}^r = M_{max}/M_{non}$ is the relative torque of the magnetic clutch; $\Pi_s = M_s^r = M_s/M_{nom}$ is the relative braking torque of the screen; $\Pi_l = M_l^r = M_l/M_{nom}$ is the relative load-induced torque; $\Pi_{em} = M_{em}^r = M_{em}/M_{nom}$ is the relative electromagnetic torque of the electric motor; and $\Pi_0 = M_0^r = M_0/M_{nom}$ is the relative no-load torque of the electric motor.

The parameter Π_ω characterizes the rate of the starting acceleration of the machine, Π_I is the ratio of the moments of inertia of the driving and driven parts of the machine, and Π_c, Π_s, Π_l, Π_{em}, and Π_0 are the ratios of the effective rotational torques of the machine and the nominal torque of the asynchronous electric motor.

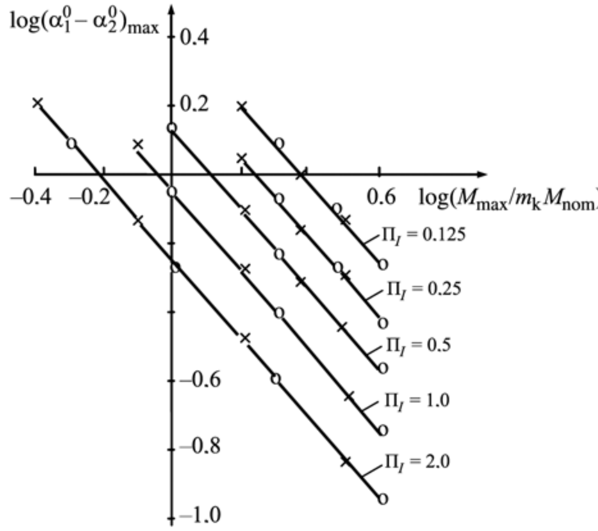

Fig. 2. Plot showing relationship between maximum angle of mismatch $(\alpha_1 - \alpha_2)_{max}$ and ratio $M_{max}/(m_k M_{nom})$: ○) $m_k = 2$; ×) $m_k = 2.6$.

The effect of the parameters Π_ω, Π_I, Π_c, Π_{em}, and Π_0 were determined in the first stage of the investigation of the stable operation of a machine with a magnetic clutch (the parameters Π_s and Π_l were disregarded). The parameter Π_ω was varied within the interval from 5 to 25, ensuring the possibility of variation in the parameter Π_I from 0.125 to 2.0. This interval of the ratios of the moments of inertia of the driving and driven parts of the machine was selected on the basis of design experience gained with hermetically sealed machines with a magnetic clutch). When $\Pi_I < 0.125$, it is necessary to use additional devices to reduce the starting torque of the electric motor in order to avoid mismatch between the half couplings of the magnetic clutch; when $\Pi_I > 2.0$, it is necessary to employ an electric motor with a power on the high side. The parameter Π_c was varied within the interval from 1.0 to 8.0. The maximum value $\Pi_c = 1.0$ was selected from the condition whereby the torque induced by the load on the effective member of the machine should not exceed the nominal torque of the electric motor, whereupon operation of the machine is provided by a magnetic clutch with a static torque equal to the nominal torque of the electric motor. The maximum value $\Pi_c = 8.0$ was selected from the condition whereby the total moment of inertia of the rotating driving and driven parts of the machine does not exceed the limiting value for the electric motor. Values of the parameter Π_{em} of from 1.9 to 3.0 (the ratio of the maximum torque of the electric motor to the nominal torque) are given in the reference literature. For the investigation, it was assumed that $\Pi_{em} = 2.0$ and 2.6 (frequently encountered values). The parameter Π_0 was assumed equal to 1% of the nominal torque of the electric motor during the course of all investigations.

It was established as a result of the investigations that the values of the initial and maximum angles of mismatch between the half couplings do not change as the parameter Π_ω varies for constant Π_I, Π_c, and Π_{em}. The time of the machine's starting acceleration and the number of oscillations of the half couplings of the magnetic clutch increase with increasing Π_ω. Π_ω was set equal to five in continuing studies.

Π_I, Π_c, and Π_{em} are basic parameters exerting an influence on the performance of the hermetically sealed machine. The parameter Π_{em} can then be denoted by m_k as in [4]. As the investigations indicated, the maximum value of the angle of mismatch between the half couplings is observed at the moment when the electric motor attains maximum torque; it is therefore expedient to investigate the effect of the parameters Π_c and m_k on the performance of the machine in the form of the ratio Π_c/m_k, i.e., $M_{max}/(m_k M_{nom})$, where the product $(m_k M_{nom})$ is the value of the maximum torque of the electric motor.

The relationship between the maximum angle of mismatch on $M_{max}(m_k M_{nom})$ for different Π_I values is a family of straight lines (Fig. 2). For constant Π_I, an increase in the parameter m_k will lead to an increase in the maximum angle of mismatch between the half couplings during the starting acceleration, and when $(\alpha_1 - \alpha_2)_{max} = 0.5\pi$, operation of the machine is considered unsteady, since addition of the load on the driven member may break the magnetic bond between the half cou-

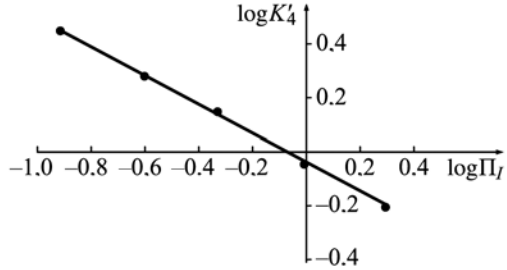

Fig. 3. Plot showing dependence of K_4' on parameter Π_I.

plings. A decrease in the angle of mismatch is possible when either the torque of the clutch, or the moment of inertia of the rotating parts of the driving member increases. If the parameter Π_I is small, i.e., the moment of inertia I_2 of the rotating driven parts substantially exceeds I_1, the torque of the magnetic clutch is appreciably increased.

If a screen formed from a conducting non-magnetic material is placed in the air gap between the half couplings of the magnetic clutch, eddy currents are applied to the latter during the machine's operation, and a braking torque of the screen, which affects the pattern of motion of both the driving and driven parts, develops. During the investigations, the parameter Π_s was varied from 0 to 1.0, while the parameters Π_I, Π_c, and m_k were held constant. The minimum value of $\Pi_s = 0$ is assigned for the case when there is no screen in the gap between half couplings (the clutch functions as a protective device), or a screen formed from a non-magnetic non-conducting material (polypropylene, carbon-reinforced plastic, etc.) exists; the maximum value $\Pi_s = 1.0$ is adopted from the condition whereby the electric motor operates normally: the load on the motor should not exceed the nominal torque. In this stage of the investigation, Π_l was assumed equal to zero.

The investigations demonstrated that the maximum angle of mismatch under the braking torque of the screen increases negligibly (the effect on the driving and driven parts is the same, and during start-up acceleration they equalize one another), and the time of the starting acceleration is extended.

In the majority of machines with magnetic clutches, the load is either constant (hermetically sealed hoists), or close to a ventilation load (mixers, pumps, gas blowers). Only constant and ventilation loads were therefore investigated. The torque induced by the load acts on the driven parts of the machine and ensures the existence of an angle of mismatch between the half couplings at the moment of the starting acceleration, and in the steady-state operating regime. The maximum Π_l value under a constant load was limited by the ratio $M_{\text{em.min}}/M_{\text{nom}}$, since starting acceleration of the machine does not occur under a heavy load ($M_{\text{em.min}}$ is the minimum torque of the electric motor [4]). In that case, the electric motor develops maximum rotational speed corresponding to its minimum torque. For the majority of electric motors, $M_{\text{em.min}}/M_{\text{nom}} = 0.8$. The parameter Π_l was varied from 0 to 0.8 under a constant load.

Under a constant load, the increase in the maximum angle of mismatch for the same values of the parameter Π_I decreases with increasing torque of the clutch, and the increase in the angle increases with decreasing torque of the clutch.

A ventilation load applied to the driven parts of the machine will affect the angle of mismatch to a lesser degree than a constant load, since the ventilation-induced torque increases smoothly from zero to the maximum value. During the investigations, the parameter Π_l was varied from 0 to 1.0.

The mathematical description of the variation in maximum angle of mismatch (see Fig. 2) will take on the form:

$$\log(\alpha_1^{\text{r}} - \alpha_2^{\text{r}})_{\max} = \log K_4' - 1.2\log\left(\frac{M_{\max}}{m_{\text{k}} M_{\text{nom}}}\right), \tag{4}$$

where log K_4' is a constant quantity dependent on the parameter Π_I.

The mathematical expression for the relationship between K_4' and the parameter Π_I (Fig. 3) assumes the form:

$$\log K_4' = \log 0.85 - 0.6\log(I_1 / I_2). \tag{5}$$

After substitution of Eq. (5) in Eq. (4) and simple mathematical transformations, we obtain the following equation for determination of the maximum angle of mismatch in deg:

$$(\alpha_1 - \alpha_2)_{\max} = \frac{0.85}{(I_1/I_2)^{0.6}\left(\dfrac{M_{\max}}{K_1' m_{\mathrm{k}} M_{\mathrm{nom}}}\right)^{1.2}}. \tag{6}$$

For series-produced AO2 electric motors, it is necessary to introduce a correction factor K_1' [5]; for series-produced 4A, AIR, AIM, AI, and VAO electric motors, $K_1' = 1$.

If a current-conducting screen formed from a non-magnetic steel is placed in the air gap between the half couplings of the magnetic clutch, the maximum angle of mismatch is determined from the expression

$$(\alpha_1 - \alpha_2)_{\max.\mathrm{s}} = \frac{0.85}{(I_1/I_2)^{0.6}\left(\dfrac{M_{\max}}{K_1' m_{\mathrm{k}} M_{\mathrm{nom}}}\right)^{1.2}} + 0.125\frac{M_{\mathrm{s}}}{M_{\mathrm{nom}}}. \tag{7}$$

Under a constant load, the expression for determination of the maximum angle of mismatch assumes the form:

$$(\alpha_1 - \alpha_2)_{\max.\mathrm{c}} = \frac{0.85}{(I_1/I_2)^{0.6}\left(\dfrac{M_{\max}}{K_1' m_{\mathrm{k}} M_{\mathrm{nom}}}\right)^{1.2}} + \frac{1.7M_{\mathrm{nom}}}{M_{\max}}. \tag{8}$$

Under a ventilation-induced load, the expression for the maximum angle of mismatch will take on the form

$$(\alpha_1 - \alpha_2)_{\max.\mathrm{v}} = \frac{0.85}{(I_1/I_2)^{0.6}\left(\dfrac{M_{\max}}{K_1' m_{\mathrm{k}} M_{\mathrm{nom}}}\right)^{1.2}} + \frac{0.27(M_l/M_{\mathrm{nom}})}{(1.2)^L}, \tag{9}$$

where $L = \Pi_{\mathrm{c}} = M_{\max}/M_{\mathrm{nom}}$.

For the combined action of the braking torque of the screen and the load-induced torque, Eqs. (8) and (9) will take on the form:

$$(\alpha_1 - \alpha_2)_{\max.\mathrm{c}} = \frac{0.85}{(I_1/I_2)^{0.6}\left(\dfrac{M_{\max}}{K_1' m_{\mathrm{k}} M_{\mathrm{nom}}}\right)^{1.2}} + 0.125\frac{M_{\mathrm{s}}}{M_{\mathrm{nom}}} + \frac{1.7M_{\mathrm{nom}}}{M_{\max}}; \tag{10}$$

$$(\alpha_1 - \alpha_2)_{\max.\mathrm{v}} = \frac{0.85}{(I_1/I_2)^{0.6}\left(\dfrac{M_{\max}}{K_1' m_{\mathrm{k}} M_{\mathrm{nom}}}\right)^{1.2}} + 0.125\frac{M_{\mathrm{s}}}{M_{\mathrm{nom}}} + \frac{0.27(M_l/M_{\mathrm{nom}})}{(1.2)^L}. \tag{11}$$

The maximum value of the mismatch angle calculated from Eqs. (10) and (11) should not exceed 0.5π deg in order to avoid breaking of the magnetic bond between the half couplings.

During the machine's start-up, the ventilation load does not attain the maximum value, and its effect on the angle of mismatch between the half couplings is therefore less significant that the effect of the constant load.

The effect of the braking torque of the screen on the maximum angle of mismatch is insignificant.

In designing machines with a magnetic clutch, it is desirable that the ratio of the moments of inertia of the driving and driven parts be equal to, or greater than unity, ensuring normal operation of the electric motor driving the machine (the limiting value of the moment of inertia induced by the load on the electric motor is not exceeded). The dimensions of the magnetic clutch and the torque transmitted to it are minimal in that case. A ratio of moments of inertia of the rotating parts, which is less than unity, will lead to in an increase in the torque transmitted by the clutch, and its geometric dimensions, and to an increase in the moment of inertia of the load on the electric motor.

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